# Assessing the short-to medium-term supply risks of clean energy minerals for China

Yanjing Zhou [a,b], Jianwu Li [b,*], Gaoshang Wang [b], Shouyu Chen [a], Wanli Xing [b], Tianjiao Li [c]

[a] Faculty of Earth Resources, China University of Geosciences, Wuhan, 430074, China
[b] Research Center for Strategy of Global Mineral Resources, Chinese Academy of Geological Sciences, Beijing, 100037, China
[c] China University of Geosciences(Beijing), Beijing, 100083, China

## A B S T R A C T

Concerns about both climate change and energy security stress the importance of clean energy technologies. This paper examines the minerals used in clean energy technologies (mainly solar energy, wind energy and electric vehicles), of which 12 elements are identified to be dependent on resources outside China. Therefore, a quantitative, relative assessment of short-to medium-term supply risks is measured for 12 elements by analyzing the following factors: country concentration, import reliance, import concentration, country risk, depletion time, companion metal fraction, recycling potential and substitutability. The results highlight four elements to present a high risk, namely: tin, cobalt, chromium and nickel; while lithium, copper and titanium are the most impossible to encounter a supply disruption; the remaining five elements (silver, cadmium, zirconium, manganese and selenium) appear a moderate risk. An uncertainty analysis using Monte Carlo simulation shows a robust reliability on most of the 12 elements except for cobalt and tin. Mitigation strategies to alleviate the potential supply disruption are also discussed, such as broadening import sources; investing domestic and global mining; recycling and substitution; stockpiling.

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## 1. Introduction

Continuing rapid growth of the Chinese economy has resulted in a lot of fossil energy consumption in China, making China to be the largest primary energy consumer and $CO_2$ emitter. On the one hand, China's import reliance on imported oil had a rapid growth from 23% in 1990 to 65% in 2016 (Xu and Lin, 2018), while the global oil will be exhausted after 50 years (BP, 2018). On the other hand, China has long been in a passive position in the international climate change negotiations with tremendous pressure. Therefore, energy structure transformation is the only choice for China's sustainable development under the dual pressure of energy crisis and reducing $CO_2$ emissions. Broadening clean energy deployment in China would significantly reduce greenhouse gas emissions and its associated climate impacts, which is of great importance to improve global climate change. However, clean energy technologies are more metal-intensive than traditional energy systems and they unfortunately are often dependent on minerals whose demand will increase quickly under the shift in the global energy sector towards low carbon technologies (de Koning et al., 2018). An intense competition for limited clean energy minerals among countries around the world can be expected in the near future.

With the improving awareness of the importance of clean energy to mitigate energy crisis and reduce $CO_2$ emissions, many researches on supply risks for clean (low-carbon or green) energy related elements have been conducted deeply (DOE, 2011; Goe and Gaustad, 2014; Grandell and Thorenz, 2014; GSA, 2013; Helbig et al., 2016; Helbig et al., 2018; Moss et al., 2013a,b; MRS and APS, 2011; Parthemore, 2011). Most supply risk studies are associated with "economic importance" and "environmental factors" to a criticality assessment and the aims can be categorized into four categories: national level studies (Blengini et al., 2017a,b; NRC, 2008; Yang et al., 2013), global level studies (Wang C et al., 2018), future technology studies (Grandell and Thorenz, 2014) and entrepreneurial perspective studies (Duclos et al., 2010). From the

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perspective of time horizon, the studies range from a "short-term" (EC, 2017) to a "long run" (Rosenau-Tornow et al., 2009), and some include both (Coulomb et al., 2015; Graedel et al., 2012). Among those studies, supply risk assessments in a qualitative (DOE, 2011; Moss et al., 2013a,b; NRC, 2008; Olivetti et al., 2017) or semi-quantitative (Helbig et al., 2016, 2018; Jasiński et al., 2018) way are more than in a quantitative way (EC, 2017; Goe and Gaustad, 2014). As can be expected from the diversity in entities, a variety of indicators and methodologies are used to evaluate supply risks for different aims, and the selection, weighting and aggregation of individual components within the supply risk assessment tend to be determined by experts or decision-makers which are all subjective. Furthermore, in respect to the geographic distribution, almost all the researches about supply risk come from developed countries (Hayes and McCullough, 2018; Jin et al., 2016), such as the United States and the European Commission have identified energy-critical elements for themselves. However, there is no knowledge about whether the material availability will be a potential constraint for broad deployment of clean energy in China.

Assessing supply risks of materials is challenging due to the complexity of influence factors and availability of data. This paper aims to assess supply risks of mineral raw materials used in clean energy quantitatively for China and to help policy-makers address material supply risk while at the same time continue to encourage clean energy development. The structure of this paper is as follows: the following part determines the raw materials of clean energy industry and selects the objections of this assessment. The specific indicators and method used are described in section 3. The evaluation results for each element are then presented and the risk sources are also analyzed. The section 5 gives a discussion on the evaluation results and puts forward measures and suggestions to reduce supply risk. The article ends with some conclusions.

## 2. Minerals in clean energy technologies and screening

Clean energy aims at utilizing renewable energy sources and improving energy efficiency. Some energy-related systems, such as wind turbines, solar energy collectors and batteries for electric vehicles (EVs) are materials intensive. Our focus is on the energy technologies with the potential for large-scale deployment as well as with high dependency on mineral raw materials.

The three technologies in Table 1 are selected for the following reasons. First, they are expected to be deployed substantially both in China and in the world over the next 10 years. More than half of the increase in renewable energy in 2017 comes from wind power, and more than one-third comes from solar energy (BP, 2018). Second, China's "the 13th Five-Year Plan for Renewable Energy Development" lists wind power and solar power generation as the top priority for the development of renewable energy in the future. In addition, as an important clean technology with high market penetration, the EVs have aroused significant attention from Chinese government. The production of EVs reached 794 thousand in 2017, while China's "Medium-to long-term development plan for automobile industry" sets a goal of 2 million and 7 million in 2020 and 2025. Batteries technology is paramount to EVs performance and two types of battery, namely nickel-metal hydride batteries (NiMH) and lithium-ion (Li-ion) batteries are under consideration, as they currently dominate the hybrid electric vehicles (HEV) market and plug-in hybrid electric vehicles (PHEVs) and battery electric vehicles (BEVs) market, respectively (Moss et al., 2013a,b; Grandell et al., 2016). Among all the cathode materials in Li-ion batteries, lithium nickel cobalt aluminum oxide (NCA) and lithium nickel manganese cobalt oxide (NMC) prevail the others.

The minerals used in the three technologies have been identified according to previous studies (DOE, 2011; Eggert R, 2017; Moss et al., 2013a,b; Shou et al., 2017; Wang C et al., 2018) and the selection focus exclusively on mineral raw materials whose global demand could be increased substantially with the deployment of relevant technologies.

There are 27 minerals identified in the three technologies as shown in Table 1. However, the one with net import reliance equaling to zero is excluded from our assessment, such as In, Ge, Ga, rare earth (Ce, Dy, La, Nd, Pr, Sm), Te, Mo, Al, Mg, graphite and Si (Gulley et al., 2018). So the remaining 12 elements, i.e. Se, Sn, Ag, Li, Co, Ti, Ni, Mn, Cr, Cu, Cd and Zr, are selected for further analysis.

## 3. Methods − evaluation model and data sources

Assessing the supply risk at different stages of the supply chain, i.e., mining and refining, can lead to different results based on changes in the concentration of production. In principle the stage with the highest supply risk in the material supply chains should be selected for evaluating. For example, China, in a shortage of cobalt resources, is the largest producer of refined cobalt by importing a large number of cobalt ores and concentrates, therefore, the mining stage has the highest risk and it should be considered. The supply chain approach (Blengini et al., 2017a,b; Graedel et al., 2015) has been adopted by screening the weakest points of 12 elements, and here refining stage is only chosen for Se and Cd because they are generally recovered from refining stages of host metals (Cu, Zn) and the mining production is unavailable. The other 10 elements are assessed for mining stage, which is in accordance with the fact that China has been the largest manufacturing country in the world whose material-intensive manufacturing industries depend on imported raw materials (Gulley et al., 2018).
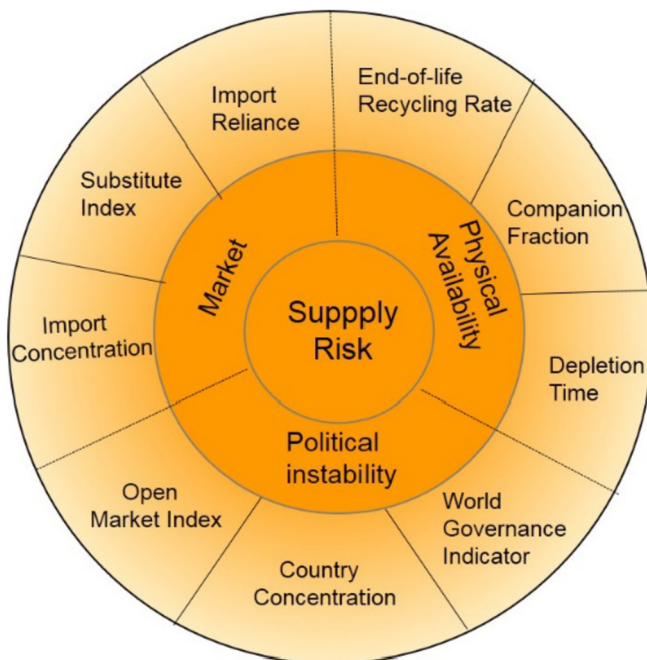
### 3.1. Indicators

In this paper, we define supply risk to be a relative concept measuring the likelihood of supply disruption and attempt to compare elements against each other to determine which are the most vulnerable to supply disruptions. This article mainly focuses on the supply risk from the perspective of China for short-to medium-term (5−10 years) and the selection of indicators (see Fig. 1) for evaluating supply risks is a synthesis of previous studies (Achzet and Helbig, 2013; Jasiński et al., 2018). Eight measures of mineral supply risk are used according to applicability, relevance, accessibility and credibility of the data, i.e. global supply concentration, import reliance, import concentration, country risk (World Governance Indicator & Open Market Index), depletion time, companion metal fraction, recycling potential and substitutability. Their meanings and effects on supply risk will be analyzed in the following.

The country concentration is most used among all the indicators of supply risk (Achzet and Helbig, 2013; Jasiński et al., 2018). It means that if the production is concentrated in a few countries, the metal's supply will be easily disrupted because of the main suppliers' strategic limitations to trade, which in turn create large economic uncertainties. This is especially true if the country's political stability and economic openness are extremely poor. On the basis of previous studies, this research combines global supply concentration with the assessment of country risk using the Herfindahl-Hirschman index (HHI). The country risk measures the potential disruption of a mineral supply in the form of poor governance and closed economies, which is represented by the World Governance Indicators (WGI) (Graedel et al., 2012) and the Open Market Index (OMI) (Coulomb et al., 2015). The WGI is a set of six indicators quantifying different dimensions of governance and indicating the probability of a destabilization of the administration by inner or outer influences. The openness of economies is an

**Table 1**
Minerals used in wind energy, solar energy and batteries for EVs.

| Minerals | Wind energy | Solar energy | Batteries for EVs | |
| --- | --- | --- | --- | --- |
| | | | Li-ion batteries | NiMH batteries |
| Ag | | ● | | |
| Al | | ○ | ○ | ○ |
| Ce | | | | ○ |
| Cd | | ● | | |
| Co | | | ● | |
| Cr | ● | | | ● |
| Cu | ● | ● | ● | ● |
| Dy | ○ | | ○ | |
| Ga | | ○ | | |
| Ge | | ○ | | |
| Graphite (C) | ○ | | ○ | |
| In | | ○ | | |
| La | | | | ● |
| Li | | | ● | |
| Mg | | | | ○ |
| Mn | ● | | ● | ● |
| Mo | ○ | ○ | | |
| Nd | ○ | | ● | ● |
| Ni | ● | | ● | ● |
| Pr | ○ | | | ● |
| Se | | ● | | |
| Sn | | ● | | |
| Sm | | | | ○ |
| Te | | ○ | | |
| Si | | ○ | | |
| Ti | | | | ● |
| Zr | | | | ● |



**Fig. 1.** Supply risk indicators used in this study.

important factor that mitigates supply risk, and this paper adopts the OMI to capture the extent to which countries are genuinely open economies. The OMI consists of trade openness, trade policy, Foreign Direct Investment (FDI) openness and trade enabling infrastructure. In the case where an OMI evaluation is not available, we select a minimum value of 2 (where 1 is the least open, 6 is the most open and no score falls in the very weak category between 1 and 1.99 out of 6) because the missing economies in the OMI study only account for 10% of the trade and investment worldwide. The global supply concentration, expressed by the HH, has been adjusted by the country's WGI and OMI and calculated as follows:

$$\left(HHI_{WGI,OMI}\right)_{GS} = \sum_{C} (S_C)^2 \sqrt{WGI_C * OMI_C} \tag{1}$$

where GS represents the global supply; $S_C$ is the share of country c in the global supply of the raw material considered; $WGI_C$ represents the scaled World Governance Indicators of country c; $OMI_C$ represents the scaled Open Market Index of country c.

Import reliance (IR) is an important indicator of supply risk for national level, which is fundamental to make a distinction among raw materials that are essentially imported and that are essentially sourced domestically (Blengini et al., 2017a,b). It is a measure to judge a country's self-sufficiency and dependency on foreign resources. Here we calculate it based on the following equations:

$$IR = \frac{I - E}{P + I - E} \quad (2)$$

$$or \ IR = \frac{C - P}{C} \quad (3)$$

where I represents imports; E represents exports; P represents domestic production; and C represents consumption. The selection of equation is subjected to the availability of data.

Import concentration reflects the real sources of China's import reliance on raw materials, which has an important effect on the supply risk, such as the supply risk of a metal with high import reliance and a low import concentration is smaller than the one who has same import reliance with a high import concentration. Furthermore, the countries that import raw materials to China usually differ from the original producers. This also explains the necessity of using the indicator. The calculation of import concentration is the same as the global supply concentration in Eq. (1).

The depletion time (DT), a dynamic property, changing with geological discoveries, new technologies, and new applications (Graedel et al., 2012) also has an effect on supply of materials from a medium-term perspective. In the paper by Jasiński et al. (2018), this indicator was used in 11 studies and second only to country concentration. To some extent, DT can reflect the availability of a metal relatively if not absolutely. Compared with other "snapshot in time" indicators, it represents a medium-term situation of raw materials. Here we use the ratio of reserves to production to calculate the depletion time and both of the data come from the United States Geological Survey (USGS). We assume when the production-to-reserves ratio equals 50, the index remains unchanged and minerals with less than 50 years will be given a relatively higher supply risk value. This is in line with the approach proposed by Organization for Economic Co-operation and Development (OECD) (Coulomb et al., 2015). The depletion time indicator is calculated according to the following equation:

$$DT = \sqrt{50 * GP/GR} \quad (4)$$

where DT represents depletion time; GP represents global production; GR represents global reserves.

Most of the metals that are essential for clean technologies are coproduced with other metals: cadmium with zinc, selenium and cobalt with copper (Elshkaki and Graedel, 2015; Nassar et al., 2015). The elasticities of companion metals are directly limited by the extraction and processing of the main metals because their demand and price are usually much lower than that of host metals. Just as (Nassar et al., 2015) said that the supply of a companion metal is often not significantly influenced by changes in its demand but by the production of host metals. So if a metal has no independent deposit and all of its production is companioned with others, its supply can face special risk.

As an important source of supply, the recycling can partially compensate the reduction of primary supply. Here we use the recycling from "old scrap" as a medium-term indicator. In addition, substitutability is another risk-reducing factor and gives a measure of the ease of shift in demand from one metal to another (Helbig et al., 2016). However it is difficult to identify the metal's substitutes in each application and to quantify the substitute index. The results of substitute index in the EC report can be used regardless of the slight discrepancy on a metal's consumption structure between China and the EU.

## 3.2. Aggregation

The aggregation of the risk factors mentioned above remains a major challenge. Many studies aggregate the indicators by calculating the weighted average while the weighting of single indicators is different depending on experts or researchers (Achzet and Helbig, 2013). Since the launch of the "raw material initiative" in 2008, the EU had published three lists of key raw materials in 2011, 2014 and 2017 respectively, and revised the method of critical assessment of raw materials in 2017. The revised methodology has gone through an extensive review and feedback period involving key actors such as the EC and members of the Ad-Hoc Working Group on Defining Critical Raw Materials (AHWG), including representatives of the EU Member States, industry and scientific experts (EC, 2017). The EC's method will be adopted with the depletion time and by-product dependency introduced because it is less dependent on expert judgment but focuses on clearly quantifiable figures (Glöser et al., 2015), and therefore, it is well accepted by many studies (Coulomb et al., 2015; Daw, 2017; Knašytė et al., 2012), and it is also practicable for a large number of minerals and many countries given the current availability of data. The revised equation for calculating the supply risk (SR) for raw materials is provided in Eq. (5):

$$SR = \left[ (HHI_{WGI,OMI})_{GS} * \frac{IR}{2} + (HHI_{WGI,OMI})_{CH,S} * \left( 1 - \frac{IR}{2} \right) \right. $$
$$\left. \times \right] * DT * SI * (1 - EOL_{RR}) * CF \quad (5)$$

where CH,S represents the import sources of China and the data is from the UN Comtrade Database; SI represents substitution index of a metal; $EOL_{RR}$ represents end-of-life recycling rate, which equals the ratio of secondary production of a material (from old scrap) to consumption and the data is collected through relevant literature and research reports; CF represents companion metal fraction.

## 3.3. Data sources

Information on global reserves and annual production of the 12 elements are provided by the USGS and the trade data come from the United Nations Comtrade Database (UNCD). The WGI and OMI of all countries are published by the World Bank and the International Chamber of Commerce, respectively. The data of companion metal fraction (CF) come from Nassar's paper (Nassar et al., 2015), which evaluated companionality for 62 metals and metalloid. The substitute indexes of 12 elements are obtained from the results of the EC report (EC, 2017). However, there are inconsistencies in data sources of import reliance and recycling rates. Table 2 comprises the data of import reliance and recycling rates for 12 elements and the specific sources for each data are also shown.

## 4. Results and analysis

Through a comprehensive consideration of the existing researches about supply risk, the revised model based on the EU methodology will be adopted in this paper, which can be considered a snapshot of the situation in the 5−10 years. The highest quality data that we have tried our best to obtain for all indicators of 12 elements are the basis of the results reliability.

## 4.1. Supply risk data

We assess the supply risks for the 12 elements on the basis of the nine indicators aforementioned. Table 3 gives a summary of the

**Table 2**
Dataset of import reliance and recycling rates for 12 elements.

| Elements | Units Tons | Net import (UNCD) | Production | Sources | Consumption | Sources | IR % | EOL-RR % | Sources |
|---|---|---|---|---|---|---|---|---|---|
| Co | metal | 37698 (CRU) | 873 | CRU | | | 97.7 | 13.5 | Liu et al. (2018) |
| Cr | metal | | 35000 | USGS | 5266519 | UNCD, USGS | 99.3 | 15.0 | b |
| Zr | concentrates | 1008622 | 140000 | USGS | | | 87.8 | 0.0 | b |
| Se | metal | 1243 | 720 | a | | | 63.3 | 0.0 | Graedel et al. (2011) |
| Sn | metal | | 92000 | USGS | 191415 | WBMS | 51.9 | 5.0 | c |
| Mn | metal | 6789850 | 2330000 | USGS | | | 74.5 | 10.0 | b |
| Li | $Li_2CO_3$ | 69844 | 10646 | USGS | | | 86.8 | 0.0 | b |
| Ni | metal | | 98000 | USGS | 1062800 | | 90.8 | 12.0 | b |
| Ag | metal | | 2884 | USGS, WSS | 6020 | WSS | 52.1 | 7.0 | WSS |
| Ti | concentrates | 1860000 | 3920000 | Antaike | | | 32.2 | 0.0 | b, c |
| Cu | metal | | 3836000 | WBMS | 11642230 | WBMS | 67.1 | 21.0 | c |
| Cd | metal | 5547 | 8090 | a | | | 40.7 | 20.0 | Graedel et al. (2011) |

WBMS: World Bureau of Metal Statistics; WSS: World Silver Survey; a: Chinese Academy of Geological Sciences, 2016a; b: Chinese Academy of Geological Sciences, 2016b; c: Compilation of nonferrous metals industry statistics of China (2016).

**Table 3**
Supply risk indicators before normalization.

| Indicator | Country Concentration | Import Concentration | WGI | | OMI | | IR | EOL$_{RR}$ | SI | CF | DT |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Dimension | HHI | HHI | Global Supplier | Import Country | Global Supplier | Import Country | % | % | qualitative | % | years |
| Co | 3454 | 7923 | −0.98 | −1.43 | 2.21 | 2.01 | 97.7 | 13.5 | 1.0 | 94 | 56 |
| Cr | 2517 | 5468 | −0.34 | −0.30 | 3.13 | 3.09 | 99.3 | 15.0 | 1.0 | 2 | 12 |
| Zr | 2208 | 2771 | 0.72 | 0.49 | 3.34 | 3.27 | 87.8 | 0.0 | 1.0 | 100 | 51 |
| Se | 2352 | 1613 | 1.09 | 0.64 | 3.83 | 3.78 | 63.3 | 0.0 | 0.94 | 100 | 45 |
| Sn | 2101 | 9913 | 0.67 | −0.83 | 3.58 | 2.00 | 51.9 | 5.0 | 0.9 | 3 | 17 |
| Mn | 1766 | 2548 | 0.39 | 0.18 | 2.95 | 3.11 | 74.5 | 10.0 | 1.0 | 3 | 43 |
| Li | 3096 | 7559 | 1.03 | 1.39 | 3.54 | 3.72 | 86.8 | 0.0 | 0.91 | 52 | 444 |
| Ni | 908 | 9050 | −0.03 | −0.43 | 3.09 | 3.01 | 90.8 | 12.0 | 0.96 | 2 | 35 |
| Ag | 1038 | 2034 | −0.13 | 0.08 | 3.32 | 4.02 | 52.1 | 7.0 | 0.98 | 71 | 21 |
| Ti | 1086 | 1648 | 0.54 | −0.22 | 3.08 | 3.00 | 32.2 | 0.0 | 0.94 | 0 | 126 |
| Cu | 1255 | 1428 | 0.48 | 0.24 | 3.54 | 3.36 | 67.1 | 21.0 | 0.97 | 9 | 36 |
| Cd | 1637 | 2421 | 1.06 | 0.26 | 4.07 | 3.54 | 40.7 | 20.0 | 0.8 | 100 | 23 |

scores for all indicators before normalization, among which the high figures of indicators mean high risks, such as country concentration, import concentration, import reliance, substitute index and companion metal fraction, while the remaining indicators are the opposite.

The "country" or "import" concentration are expressed by the HHI, whose values equal the sum of the squares of the percentage market share ranging from a theoretical minimum of 0 to a maximum of 10000. It is generally believed that the market is highly concentrated when the value of HHI is higher than 2500. Country concentration of the 12 elements ranges from 908 for Ni to 3454 for Co and Cr follows behind Co with the value of 2517 as shown in Table 3. Fig. 2 shows that the top three producers of 8 elements (Co, Li, Mn, Zr, Se, Cr, Sn, Cd) account for more than 50%, indicating a relatively concentrated global supply. Import concentration is generally higher than country concentration. The largest import concentration value reaches 9913 for Sn meaning that China almost imports all tin ores from one country (Fig. 3). Similarly, the imports of Li, Ni, Co and Cr are highly dependent on a few countries. The average value for import concentration of 12 elements is as high as 4674.

We obtain two scores of WGI and OMI for a particular element by multiplying the scores for each country by the ratio of annual production and the ratio of annual import net weight. The WGI score is given on a scale between −2.5 (very unstable) and 2.5 (very stable) and the OMI has an original score on a range of 1 (least open) to 6 (most open). What we should explain here is that the WGI and OMI for China has been adjusted to the maximum value because we can expect the lowest political risk from domestic. From the perspective of global supply, taking cadmium as an example, whose refining is concentrated in China, Rep. of Korea, Japan and other stable and industrialized countries, has a high score of 1.06 for the WGI and 4.07 for the OMI. More than half (57%)
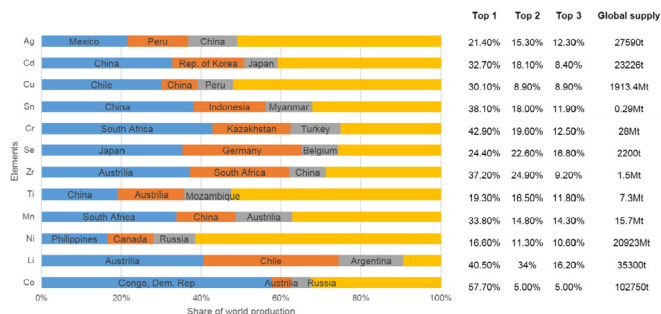


**Fig. 2.** Share of top three countries of world primary production (Data from the USGS).
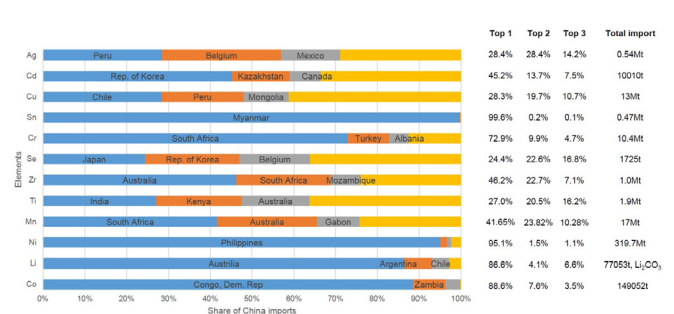


**Fig. 3.** Share of China imports held by the top producers (Data from the UNCD).

of the global production of cobalt comes from politically unstable Congo leading to the lowest scores for both the WGI and OMI. However, the WGI and OMI values of import countries for each element are generally lower than that of producing countries. This is especially true for tin and almost all imported tin ores come from Myanmar, one of the least open economies.

The import reliance for 12 elements has values between 32.2% for Ti and 99.3% for Cr. In addition, high values of import reliance are also observed for Co, Zr, Ni, Li and Cu and the value under 50% is only for Cd and Ti. End-of-life recycling rates above 20% are only for Cu and Cd, on the other hand, the recycling rates for Zr, Se and Li are negligible. 61% of Li is used in Li-ion batteries for consumption electronics (CEs) mostly in China, however, the actual recycling rate of spent Li-ion batteries from CEs is estimated to be less than 10% (Gu et al., 2017). The scarce recycling for Se and Zr due to their by-product nature and dissipative applications and are unlikely to increase in the near future (Helbig et al., 2016).

The substitutability index scores do not vary much (0.8−1) over the 12 elements. Four elements, such as Co, Cr, Zr, Mn show a strong irreplaceability. While Cd with a SI of 0.8, mainly used in nickel-cadmium batteries, is a kind of toxic heavy metal that seriously contaminates the environment and is gradually replaced by lithium batteries.

Many elements are extracted as by-products (co-products) in the mining of the host metals especially for Zr, Se, Cd, Co and Ag with the host materials being Ti, Cu, Zn, Cu/Ni and Zn/Pb/Cu/Au, respectively. Li is a co-product or by-product of other elements in continental brines and almost all brine production of Li is assumed to be as a companion of K (Kesler et al., 2012). The depletion time of reserves of the 12 elements ranges from 12 years for Cr and 17 years for Sn to 444 years for Li. Zr, Co, Ti and Li show values above 50 years.

### 4.2. Normalization and overall rating

The results of normalization for different indicators are shown in Table 4, in which the values fall into 0−1. Now all the values standardized are positively correlated with supply risks.

After introducing all the normalized indicators into Eq. (5), we obtain the overall risk values for substantial supply disruption of the 12 elements. As shown in Fig. 4, Sn shows the highest supply risk scores (0.20) followed by Co (0.13), whereas Cu and Ti have the lowest supply risk scores (both 0.01). The likelihood of supply disruption for Sn is relatively high both because of the narrow import sources (Myanmar, 99.6%) with high political risks and because of the low recycling rate and short depletion time. The high score for Co results from the high concentration of both production and import, high political risk (e.g. DR Congo), high import reliance and extraction as a by-product. For Cr and Ni, which are
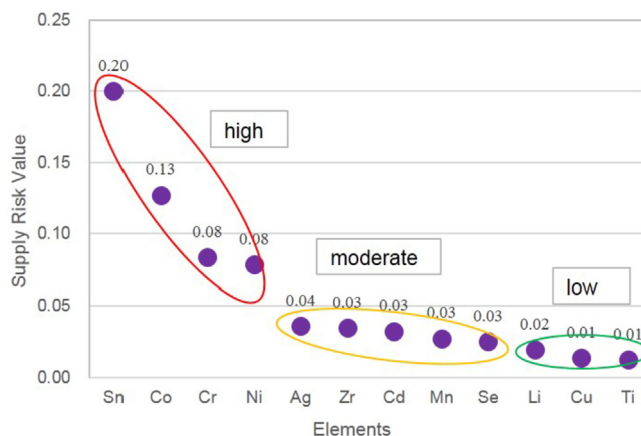


Fig. 4. Elemental supply risks after aggregating all indicators to a single value.

characterized by high import reliance, high import concentration, however, mostly extracted as a host metal, appearing the third high risks. Cu and Ti, on the contrary, both show low country and import concentrations (under 2500), low country risks as well as low supply risks. In addition, the low risk for Li benefits from the longest depletion time. The remaining five metals (Ag, Zr, Cd, Mn, and Se) have a moderate risk, the scores for which are 0.04, 0.03, 0.03, 0.03 and 0.03 respectively.

### 4.3. Uncertainty analysis

The data used in this research are inevitably with a certain degree of uncertainty, therefore, it is necessary to ascertain how much these uncertainties influence the supply risk results. The Monte Carlo simulation, which could be run through a suitable software package (Crystal Ball), is a proper way to quantify the uncertainties by repeating random sampling. We first determine a specific distribution for each indicator and the method had a detailed analysis in Graedel TE's paper (Graedel et al., 2012). For country concentration and import concentration, a lognormal distribution is to be utilized, while for the WGI and OMI, the recommended distribution type is normal. For the other indicators, the triangular distribution is recommended. At the same time, the maximum, the minimum and the most reliable data for each indicator should be inputted. Then, the Monte Carlo simulation has been run to perform 10000 instances of random-number for each element based on the inputted data and distribution. We can compute the supply risks for 12 elements by calculating the data of random sampling and as well as, the maximum, the minimum and the unit standard deviation of supply risk can be obtained.

**Table 4**
Supply risk values of nine indicators for 12 elements after normalization. Country risk results from the geomean of WGI and OMI.

| Elements | HHI-Country | HHI-Import | Country Risk | IR | EOL_RR | SI | CF | DT |
|---|---|---|---|---|---|---|---|---|
| Co | 0.35 | 0.79 | 0.69 | 0.98 | 0.87 | 1.0 | 0.72 | 0.47 |
| Cr | 0.25 | 0.55 | 0.54 | 0.99 | 0.85 | 1.0 | 0.50 | 1.00 |
| Zr | 0.22 | 0.28 | 0.44 | 0.88 | 1.00 | 1.0 | 0.73 | 0.49 |
| Se | 0.24 | 0.16 | 0.40 | 0.63 | 1.00 | 0.94 | 0.73 | 0.52 |
| Sn | 0.21 | 0.99 | 0.55 | 0.52 | 0.95 | 0.9 | 0.51 | 0.87 |
| Mn | 0.18 | 0.25 | 0.48 | 0.75 | 0.90 | 1.0 | 0.51 | 0.54 |
| Li | 0.31 | 0.76 | 0.38 | 0.87 | 1.00 | 0.91 | 0.63 | 0.17 |
| Ni | 0.09 | 0.91 | 0.51 | 0.91 | 0.88 | 0.96 | 0.50 | 0.60 |
| Ag | 0.10 | 0.20 | 0.50 | 0.52 | 0.93 | 0.98 | 0.67 | 0.77 |
| Ti | 0.11 | 0.16 | 0.51 | 0.32 | 1.00 | 0.94 | 0.50 | 0.32 |
| Cu | 0.13 | 0.14 | 0.46 | 0.67 | 0.79 | 0.97 | 0.52 | 0.59 |
| Cd | 0.16 | 0.24 | 0.40 | 0.41 | 0.80 | 0.8 | 0.73 | 0.74 |

A box-plot chart for supply risk scores of 12 elements shown in Fig. 5, which displays the median, mean and quartiles (box), is a good presentation of uncertainty for each results. The uncertainty ranges (height of boxes), e.g. Sn and Co, are higher than others and making it not assured to identify they have the higher supply risk. On the contrary, elements with the lowest supply risk scores, e.g. Cu and Ti, both of which show a flat box, meaning their simulation values are very concentrated. Overall, the assessment results are highly reliable.

## 5. Discussions and suggestions

In this paper, the supply risk is a compound index aggregating nine indicators and the correlation coefficients between normalized indicators and overall supply risk are presented in Table 5. The import concentration acts as the most positive influence followed by country risk, import reliance and country concentration, while the companion metal fraction has the lowest effect on overall supply risk. That is to say import concentration, country risk and import reliance are the main drivers of supply risk. Therefore, the elements with high import reliance and import concentration, in particular depending on the highly unstable countries, are facing higher supply risks than others. If effective measures on these aspects are taken preferentially, supply risk can be reduced significantly.

The order of highest to lowest supply risk scores are: Sn, Co, Cr, Ni, Ag, Zr, Cd, Mn, Se, Li, Cu and Ti as shown in Fig. 4. The results are not a physical expression of scarcity, but rather a relative expression of short-to medium-term supply risks. The 12 elements are divided into three categories based on the supply risk scores: (1) high risks for Sn, Co, Cr and Ni; (2) moderate risks for Ag, Zr, Cd, Mn and Se; and (3) low risks for Li, Cu and Ti.

Both Sn, Co, Cr and Ni have high import concentration among one or two countries with high political instability and low economic openness (Fig. 3). For the specific case of tin, its highest risk score mainly emerges from a high importer country risk due to the high import concentration, although other factors also play a role, e.g. low recycling rate. However, its production is evenly spaced in the world, therefore, expanding import sources can be an effective way to mitigate supply pressure in case of emergency. While in the long run, investment in global mining, as well, of course, as domestic mining to ensure future materials availability can be a useful action. For example, Li has a relatively low supply risk due to its

long depletion time (444 years), in spite of high import reliance, high import concentration, zero recycling, and extracted as by-products. In addition, the development and application of substitute materials and the recovery of secondary resources are all effective ways to mitigate the impact of supply disruption. We can calculate what changes to substitutability and recycling rates are needed to reduce supply risk scores to 0.03 (0.03 is assumed to be a relatively safe threshold) by first keeping other indicators constant and then calculate the increase in the level of recycling rates and the decrease of substitutability indexes, respectively. Fig. 6 presents the results for Co, Cr, Sn and Ni. It is obvious that very large increases in recycling rates, as well as very large reduces in substitutability, will be required. The results suggest that significant investment in Research & Development about recycle and substitution would be necessary for these minerals.

Both Ag, Zr, Cd and Se have low risks about country concentration, import concentration and country risk, which explains the moderate overall supply risks in spite of their high dependency of extraction on host metals and low recycling rates. The recycling of companions will be no significant improvement in the future because they are frequently used in small amounts in complex mixtures of materials. In addition, the best substitute for a companion metal is usually another companion metal from the same host (Nassar et al., 2015). Therefore, the best way to obtain more production of companion metals may be increasing their recovery rates from the host metal ores and this can be realized by improving the refining technologies and strengthening the awareness of enterprise to recover them rather than discard them. For Cd, whose main application, i.e. nickel-cadmium batteries, is being visibly eroded by more advanced technologies such as NiMH and Li-ion batteries and its demand will decrease in the future. In addition, Cd is significantly discarded before being fully refined into metal (Sprecher et al., 2017), and therefore, the supply risk for Cd can be ignored.

Although Li shows a low supply risk, we should pay attention to it because of the ever-increasing demand and production of Li-ion batteries in China. A very high recycling rate will be needed to extend the carrying duration of lithium reserves (Zeng X, Li J, 2013). And recycling of Li-ion batteries as well as Li is of vital significance for social-economic and environmental sustainability (Gu et al., 2017). Both improvement of collection system and recycling technology are helpful to sustain the lithium industry.

Furthermore, we can learn some lessons from Japan, a resource-poor country dependent on imports for supply of all its critical metals (Nansai K et al., 2017). For those elements with high import reliance on unstable countries, a safety access to raw materials can be assured through bilateral and multilateral trade agreements and setting up long term supply agreements with resource-rich countries (Barteková E et al., 2016). In terms of recycling and substitution, the linkages among industry-university-government as well as collaboration across up-and downstream sides of the supply chain should be strengthened and the government should take a dominant role. Also improvements in extraction, refining and manufacturing processes can help decreasing import reliance on raw materials. R&D proves the most important in this respect. In addition, stockpiling of materials can hedge against short-term supply risk effectively. However, the amount of stockpiling must be in response to the degree of import reliance, to the unavailability of substitutes and to the high geological concentration of global production. All in all, an active, comprehensive policy system is of great significance in tackling supply risk.

Referring to the methodology in this paper, the biggest obstacle we have encountered is data availability, which is particularly problematic for recycling rates and substitutability and the data of recycling rates are usually not updated in time. The substitutability
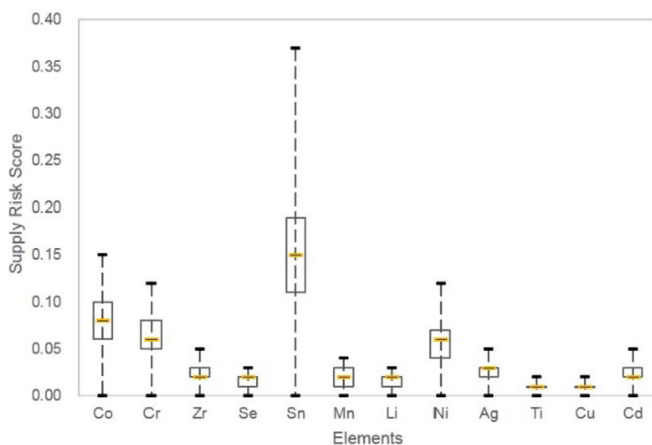
**Fig. 5.** Box-plots of supply risk scores for 12 elements.
The top line: the maximum value; the bottom line: the minimum value; the upper line of box: the third quartile; the lower line of box: the first quartile; the thick line in the middle of the box diagram: the median of the data.

**Table 5**
Correlations between the elements of the supply risk index.

|  | CF | DT | $EOL_{RR}$ | HHI-Country | HHI-Import | IR | SI | Country Risk | SR |
|---|---|---|---|---|---|---|---|---|---|
| CF | 1.00 | | | | | | | | |
| DT | −0.11 | 1.00 | | | | | | | |
| $EOL_{RR}$ | −0.13 | 0.41 | 1.00 | | | | | | |
| HHI-Country | 0.17 | −0.09 | −0.27 | 1.00 | | | | | |
| HHI-Import | −0.26 | 0.05 | −0.12 | 0.30 | 1.00 | | | | |
| IR | 0.04 | −0.05 | −0.09 | 0.66 | 0.34 | 1.00 | | | |
| SI | −0.07 | −0.05 | 0.19 | 0.45 | −0.01 | 0.52 | 1.00 | | |
| Country Risk | −0.46 | −0.28 | 0.26 | −0.01 | 0.47 | 0.21 | 0.29 | 1.00 | |
| SR | 0.03 | 0.27 | 0.17 | 0.37 | 0.69 | 0.46 | 0.14 | 0.47 | 1.00 |
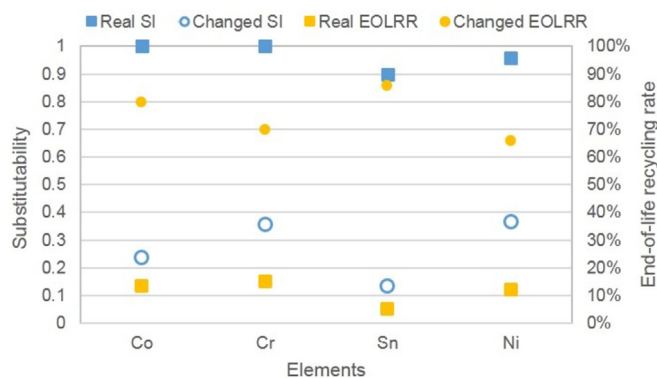


**Fig. 6.** Changes in SI and $EOL_{RR}$ needed to reduce supply risks for Co, Cr, Sn and Ni.

indexes used in this paper come from the EC report, which may lead to some deviation from the accurate overall supply risks. In addition, the standardization of companion metal fraction make it less influential on the supply risk than other studies (Graedel et al., 2012) and this will take time to test whether our analysis is right. Finally, the supply risk is a dynamic concept that will evolve as the discovery of new deposits, improvement of extraction and recycling technology and the growth of future demand (Graedel and Reck, 2016). We evaluate supply risk in this paper mainly from the short-to medium prospective, while the indicator of future demand, which can be a problem for continuous raw material supply, is not taken into account. In summary, more accurate data and improvements in the methodology may, in the course of time, raise the accuracy of the results.

## 6. Conclusions

This paper offers a quantitative assessment of supply risk using a set of nine indicators, which were chosen on the basis of a broad literature survey. The aggregation of the normalized indicator values gives a set of relative supply risk scores on a scale of 0.01–0.20. For Li, Cu and Ti, the likelihood of supply bottlenecks occurring over the next decade is found to be low. Five elements (Ag, Zr, Cd, Mn and Se) have been given a moderate rating, mainly because of the low recycling rates and high companion metal fractions. For Zr, Cd and Se, increasing by-product recovery from host metals (e.g. Ti, Zn and Cu) refining can be an effective way to mitigate the potential supply disruptions. Mn and Ag, mainly used in steel alloys (90%) and jewellery and coins (25%) at present, both have great recycling potential and their supply can be supplemented by increasing secondary supply. The remaining four metals, e.g. Sn, Co, Cr, Ni, have been given a high risk rating, for which the high import concentration and high country risk are responsible. Supply risks for the four elements can be mitigated by expanding

import sources thereby reducing the political risks of import countries. From the long-term perspective, increasing recycling and substitution of the metals is of great significance in alleviating future risks of supply. This will need the government to offer subsides or grants to encourage recycling and substitution R&D of certain metals. While the best options for the short term unavailability are stockpiling. In a word, it is important to rationally regard the bottlenecks due to the risks of raw materials for clean energy technologies because there is time for the government and stakeholders to do something as aforementioned to mitigate the risks before the large uptake of the technologies.

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